FOREST CARBON STORAGE

This chapter describes the development of material-specific estimates of changes in forest carbon storage in EPA's Waste Reduction Model (WARM). It summarizes the approach used to estimate changes in forest carbon storage in managed forests resulting from source reduction and recycling of wood and paper products.

1 A SUMMARY OF THE GREENHOUSE GAS IMPLICATIONS OF FOREST CARBON STORAGE

Forests absorb (i.e., sequester) atmospheric carbon dioxide (CO_2) and store it in the form of cellulose and other materials. In the early stages of growth, trees store carbon rapidly; consequently, as tree growth slows, so does carbon sequestration. Trees naturally release carbon throughout their life cycle as they shed leaves, branches, nuts, fruit, and other materials, which then decay; carbon is also released when trees are cleared and processed or burned.

When paper and wood products are recycled or the production of these materials is avoided through source reduction, trees that otherwise would be harvested are left standing in forests. In the short term, this reduction in harvesting results in more carbon storage than would occur in the absence of the recycling or source reduction. Over the long term, when forest managers find they have more trees standing resulting from reduced harvesting, they will respond by planting fewer trees; therefore, while the carbon storage effect of source reduction and recycling is high in the short term, it is less pronounced in the long term.

WARM evaluates forest carbon storage implications for all wood and paper products, which include all of the paper types in WARM,[1] dimensional lumber, medium-density fiberboard (MDF), and hardwood flooring. Paper products are primarily nondurable goods, or goods that generally have a lifetime of less than three years (EPA, 2008, p. 76). Wood products such as dimensional lumber, MDF, and wood flooring are considered durable goods because they typically have a lifetime of much longer than three years (Skog, 2008). Because of the differences in harvesting practices, use, and service life of paper and wood products, EPA analyzes the forest carbon storage implications for paper products separately from wood products.

In the United States, uptake by forests has long exceeded release, a result of forest management activities and the reforestation of previously cleared areas. EPA estimated that the 2008 annual net carbon flux (i.e., the excess of uptake minus release) in U.S. forests was about 792 million metric tons of carbon dioxide equivalent ($MMTCO_2E$), which offset about 3 percent of U.S. energy-related CO_2 emissions. In addition, about 24 $MMTCO_2E$ was stored in wood products currently in use (e.g., wood in building structures and furniture, paper in books and periodicals). Considering the effect of forest carbon sequestration on U.S. net GHG emissions, the data clearly showed that a thorough examination was warranted for use in WARM.

This chapter summarizes the methodology, approach, and results of EPA's analysis of forest carbon storage. The next section outlines the overall methodology, including the key components in the assessment of changes in forest carbon storage. Sections 3 and 4 summarize forest carbon storage estimates for source reduction and recycling for paper and wood products. Section 5 outlines the limitations associated with EPA's analysis of forest carbon storage.

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[1] Corrugated containers, magazines/third-class mail, newspapers, office paper, phonebooks and textbooks.

2 FOREST CARBON STORAGE METHODOLOGY

EPA estimates the net change in forest carbon storage from source reduction or recycling of forest products by evaluating three components:

1. Changes in timber harvest (i.e., trees that have been cut from the forest) as a result of changes in demand for virgin wood.
2. Changes in forest stocks as a result of changes in harvest.
3. Changes in carbon storage in the in-use product pool (for durable wood products).

These three components taken together provide the net change in carbon storage resulting from recycling or source reduction of forest products. Exhibit 1 is a flow chart explaining the approach. First, for a forest product that is recycled or source reduced instead of being put in a landfill or combusted, WARM assumes that—if demand for forest products remains constant—recycling or reuse results in a reduction in the demand for virgin timber from forests. Second, this reduction in timber harvest results in a small increase in the stock of carbon that remains in U.S. forests. Third, durable wood products remain in use for many years,[2] and are themselves a significant source of carbon storage that is tracked in the U.S. GHG Inventory[3] (EPA, 2011a). Since source reduction reduces the amount of virgin wood products that enter the market, and remanufacturing wood products into recycled products results in some loss of material, increasing source reduction or

WARM's Approach to Forest Carbon Storage

WARM adopts a waste management perspective that assumes life-cycle boundaries start at the point of waste generation (i.e., the moment a product such as paper or dimensional lumber reaches its end-of-life stage), and the methodology examines the resulting life-cycle GHG implications of alternative material management pathways relative to a baseline waste management scenario.

To evaluate forest carbon storage, WARM first assesses the amount of wood that would have been harvested from the forest with no efforts to increase source reduction or recycling. This establishes a "business-as-usual" baseline of wood harvests. Next, WARM examines how increased source reduction or recycling reduces the demand for wood harvests from the forest by avoiding the use of wood or by conserving paper and wood products relative to this business-as-usual baseline. The forest carbon storage is equal to the amount of carbon contained in wood that is not harvested as a result of increased recycling or source reduction.

In other words, rather than evaluating the entire stock and flows of carbon into and out of forests in the United States, WARM evaluates the difference, or *marginal* change, in forest carbon storage resulting from efforts to increase source reduction or recycling beyond the business-as-usual baseline. This approach is consistent with WARM's purpose of evaluating the benefits of alternative management practices relative to baseline activities.

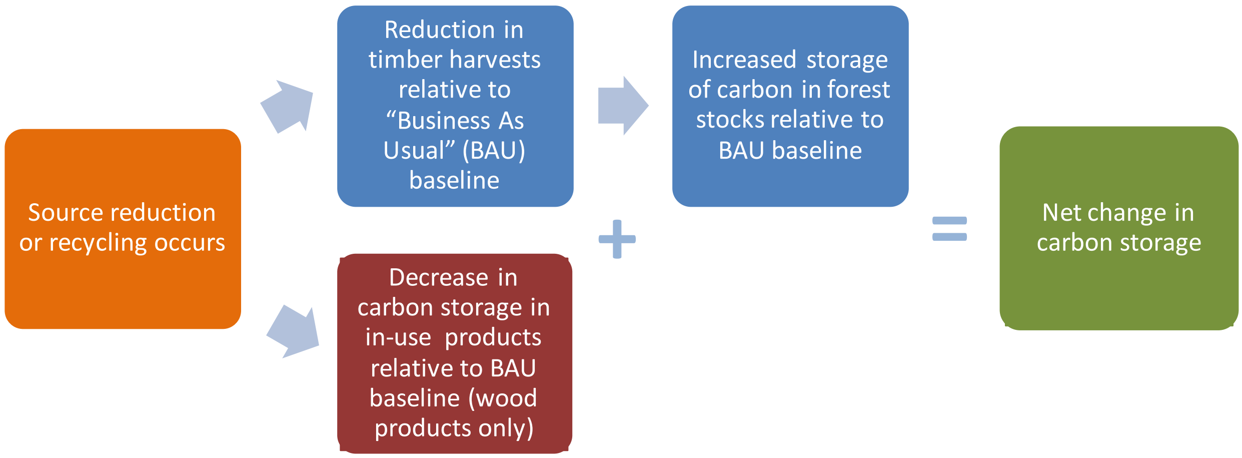
On average in the United States, timber harvests are more than compensated by replanting; therefore, baseline forest carbon withdrawals need to be considered as part of the overall carbon stocks-and-flows cycle for forest and harvested wood products. This methodology is consistent with and supported by the Intergovernmental Panel on Climate Change (IPCC) Inventory Guidelines (IPCC, 2006) that distinguish between biogenic carbon that is harvested on a sustainable basis versus non-sustainable harvest, and the fact that land use change and forestry provide a large net sink for GHG emissions in EPA's U.S. GHG Inventory (2011a).

[2] For example, Skog (2008) estimates that the half-life of wood (i.e., the amount of time it takes for half of an initial amount of wood to reach the end-of-life stage) is 100 years in single-family housing and 30 years in other end uses.
[3] Durable wood products (also known as harvested wood products) accounted for 54 metric tons of CO_2 (equivalent to 15 metric tons of carbon) in 2009. See Chapter 7 of the U.S. GHG Inventory (EPA, 2011a).

recycling decreases the amount of carbon stored in in-use products.

Consequently, for durable wood products, recycling and source reduction increase the amount of carbon that is stored in U.S. forests, but simultaneously they decrease the amount of carbon from virgin products that would have been stored in durable wood products. Together, these two factors equal the net change in carbon storage resulting from increased source reduction or recycling. Note that the decrease in carbon storage in in-use products applies only to durable (wood) products; WARM does not consider changes in the in-use product carbon pool for nondurable (paper) goods because these products have shorter lifetimes, typically less than three years, and the carbon in these goods cycles out of the in-use pool over a relatively short period.

Exhibit 1: Forest Carbon Storage Methodology



3 FOREST CARBON STORAGE AND PAPER PRODUCTS

Paper products in WARM include corrugated containers, magazines/third-class mail, newspapers, office paper, phonebooks, and textbooks. These products are short-lived, nondurable goods that are harvested primarily from forests that are grown for making wood pulp for paper production. This section describes the methodology used to evaluate the two relevant components of forest carbon storage, outlined in Section 2, for paper products: changes in timber harvest and changes in forest stock.

Paper types fall into two broad categories, mechanical- and chemical-pulp papers. Mechanical pulping involves grinding logs into wood fibers and mixing with hot water to form a pulp suspension. Chemical pulping, also known as kraft pulping, involves removing the surrounding lignin in the wood raw material during a cooking process. (Verband Deutscher Papierfabrikin e.V., 2008) Of the paper types modeled in WARM, mechanical pulp papers include newspaper and textbooks. Office paper, corrugated containers, textbooks, and magazines/third-class mail are considered chemical-pulp paper types.[4]

3.1 EFFECT OF SOURCE REDUCTION AND RECYCLING ON TIMBER HARVESTS

Several U.S. Department of Agriculture Forest Service (USDA FS) efforts have analyzed the relationship between paper recovery (i.e., recycling) rates and pulpwood harvests (i.e., wood harvested

[4] In general, shipping and packaging containers, paper bags, and printing and writing papers are manufactured from chemical pulp, while newspaper, specialty papers, tissue, toweling, paperboard, and wallboard are produced from mechanical pulp (AF&PA, 2010a).

for paper production) based on data compiled by the American Forest and Paper Association (AF&PA) and the Forest Resources Association (FRA). AF&PA collects information on the mass of recovered paper and wood pulp consumed (AF&PA, 2005) and paper and paperboard production (AF&PA, 2004). FRA publishes information on the annual amount of pulpwood received at pulp mills (FRA, 2004). Based on this information, along with assumptions about moisture content,[5] Dr. Peter Ince of USDA FS developed the following equation to relate paper recovery to pulpwood harvests (Ince and McKeever, 1995):

$$PWH = X \times \{PP - [PR \times (1 - EX) \times Y]\} \quad \text{(Eqn. 1)}$$

Where,

- *PWH* = Pulpwood harvests at 0 percent moisture content, i.e., ovendry (short tons)
- *PP* = Paper production at 3 percent moisture content (short tons)
- *PR* = Paper recovery at 15 percent moisture content (short tons)
- *EX* = Percentage of recovered paper that is exported
- *X* = Process efficiency of converting ovendry pulpwood to paper and paperboard at 3 percent moisture content, which is the ratio of finished paper to pulp, and accounts for the portion of paper and paperboard that is water and fillers
- *Y* = Process efficiency of converting recovered paper at 15 percent moisture to paper and paperboard at 3 percent moisture, which is the ratio of recovered paper to finished paper, and accounts for the water in recovered paper

The values of *X* and *Y* are based on process efficiency estimates provided by John Klungness (Research Chemical Engineer, USDA FS) and Ken Skog (Project Leader, Timber Demand and Technology Assessment Research, USDA FS). The value for *EX*, the export rate, is based on AF&PA statistics on U.S. recovered paper exports. In 2008, approximately 40 percent of recovered paper was exported from the United States (AF&PA, 2010b).[6]

EPA uses the relationship developed in Equation 1 to describe how a change in paper recovery affects pulpwood harvests. For example, if paper recovery increases by one short ton, by how much would pulpwood harvests be reduced to meet the same level of paper production in the United States? Exhibit 2 column (f) shows that increasing paper recovery by one short ton would reduce (i.e., avoid) pulpwood harvests by 0.58 short tons for mechanical pulp papers and by 0.89 short tons for chemical pulp papers. This difference results from the lower ratio of pulp to finished paper for chemical-pulp papers because the chemical pulping process in paper manufacturing removes lignin from the raw wood material.

Exhibit 2: Relationship Between Paper Recovery (i.e., Recycling) and Pulpwood Harvest (Values of Eqn. 1 Parameters)

[5] The moisture contents are pulpwood as harvested, 50 percent; paper and paperboard, 3 percent; wood pulp consumed, 10 percent; and recovered paper consumed, 15 percent. Knowing the moisture content is important to accurately gauge carbon contents of these materials.

[6] EPA included the export rate in the calculation of avoided pulpwood harvest per ton of paper recovered because the WARM analysis focuses on the United States; therefore, EPA assumed the avoided pulpwood harvest was affected only by recovered paper that stays in the United States. Recovered paper that is exported will produce a different offset for pulpwood harvests in other countries because forest management practices outside of the United States are likely to be different. The inclusion of the exported recovered paper as a factor in calculating avoided pulpwood harvest per ton of paper recovered is a conservative assumption because it results in a smaller reduction in pulpwood harvests from increased paper recovery.

(a)	(b) Ratio of Pulp to Finished Paper	(c) *X* = Process Efficiency (c = 1/b)	(d) *Y* = Ratio of Recovered Paper to Finished Paper	(e) EX (%)	(f) Avoided Short Tons PWH per Short Ton Paper Recovered (f = c × d × [1 − e])
Mechanical Pulp	0.900	1.11	0.875	40	0.58
Chemical Pulp	0.475	2.11	0.700	40	0.89

For source reduction, the change in pulpwood harvests from source reducing paper can be calculated directly from the process efficiency (X) of mechanical and chemical pulp production. This is because source reduction, by reducing consumption of paper, directly reduces paper production (PP in Equation 1) and, consequently, the amount of pulpwood harvested. Based on the process efficiency estimates in Exhibit 2, WARM estimates that one short ton of source reduction avoids 1.1 short tons of pulpwood harvests for mechanical pulp, and 2.11 short tons of chemical pulp.

3.2 EFFECT OF CHANGES IN TIMBER HARVESTS ON FOREST CARBON STOCKS

EPA bases its analysis of carbon storage on model results provided by the USDA FS using its FORCARB II model of the U.S. forest sector. USDA FS models and data sets are the most thoroughly documented and peer-reviewed models available for characterizing and simulating the species composition, inventory, and growth of forests, and the Forest Service has used them to analyze GHG mitigation in support of a variety of policy analyses. FORCARB II is a USDA FS model that simulates the complex, dynamic nature of forest systems, including the interaction of various forest carbon pools, how carbon stocks in those pools change over time, and whether the response of forest carbon is linearly proportional to harvests. To explore these questions, USDA FS ran two enhanced recycling/source reduction pulpwood harvest scenarios in FORCARB II.

The base assumptions on pulpwood harvests are derived from the North American Pulp and Paper (NAPAP) model baseline projections developed for the Forest Service 2001 Resource Planning Act Timber Assessment. To investigate the effect of small and large changes in pulpwood harvests, the Forest Service modeled two reduced harvest scenarios, which involved decreasing pulpwood harvest by 6.7 million metric tons and 20.2 million metric tons for the period 2005–2009.[7] The Forest Service selected the values of 6.7 million and 20.2 million metric tons as representative low- and high-end reductions in pulpwood harvests based on the 50-percent paper recycling rate in 2005 (EPA, 2006). Harvests in all other periods were the same as the baseline.

The relative change in forest carbon storage per unit of reduced pulpwood harvest across the two decreased harvest scenarios is virtually identical (i.e., less than 1 percent), which suggests that the relationship between forest carbon storage and reduced pulpwood harvests is not affected by the size of the reduction in pulpwood harvests over the range investigated by the two scenarios.

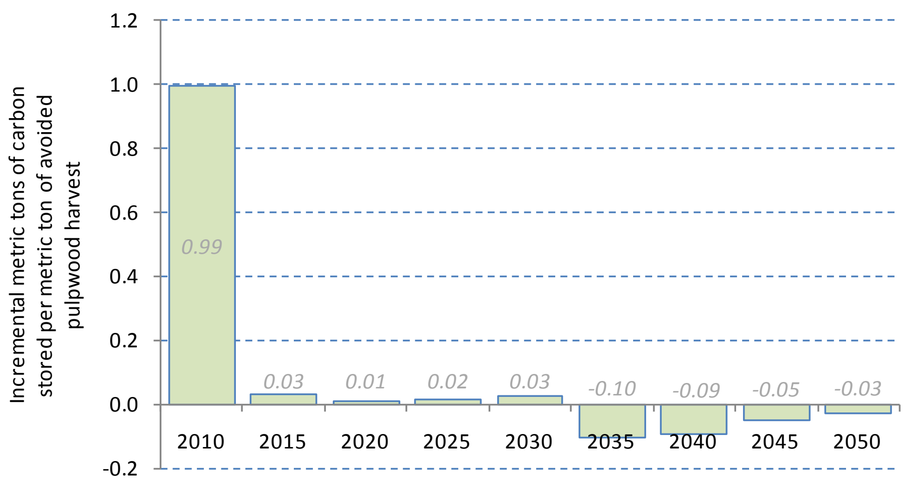
For each scenario, the Forest Service calculated the change in carbon stocks compared with the base case; the change represents the carbon benefit of reduced harvests associated with recycling or source reduction. The change in metric tons of carbon equivalents (MTCE) is divided by the incremental metric tons of pulpwood harvested and multiplied by the weight ratio of CO_2 to carbon (44/12, or approximately 3.667) to yield results in units of $MTCO_2E$ per metric ton of pulpwood not harvested (i.e.,

[7] EPA selected this timeframe because, at the time the EPA did the analysis, that period represented a short-term future time horizon over which reduced forest withdrawals could be evaluated against baseline projections.

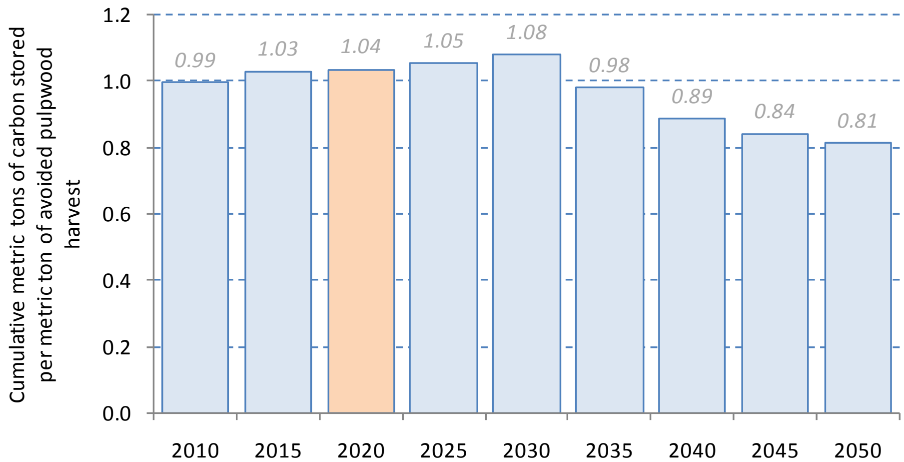
the carbon storage rate). For more details, please refer to the conversions provided in Exhibit 4 and Exhibit 5.

As shown in Exhibit 3, the cumulative carbon storage rate starts at about 0.99 MTCE per metric ton pulpwood in 2010, increases to about 1.08 MTCE per metric ton pulpwood in 2030, and declines with time to about 0.81 MTCE per metric ton pulpwood in 2050. According to EPA's detailed analysis of the FORCARB II results, the primary effect of reduced pulpwood harvests is to increase carbon stored in live trees that otherwise would have been harvested (shown by the sharp increase in carbon storage in 2010). This effect is offset to a small degree by a decrease in carbon storage in the amount of downed wood in the forest. Carbon storage in dead trees, the forest floor, and forest understory increases slightly; carbon stored in forest soils has no effect. Most of the changes in each of these pools of forest carbon peak in 2010 and moderate somewhat over the next 40 years, although the increase in carbon storage in the forest floor peaks over a longer time period in 2030. After 2030, the amount of carbon stored in live trees begins to decline, causing a reduction in forest carbon storage. This decline likely reflects the effect of market forces, which result in less planting of new managed forests in response to a lower level of demand for pulpwood harvests.

Exhibit 3: Change in Forest Carbon Storage Per Unit of Reduced Pulpwood Harvest for (a) Incremental Change in Forest Carbon Storage and (b) Cumulative Change in Forest Carbon Storage Per Unit of Reduced Pulpwood Harvest



(a)



(b)

Note: Colored bar for 2020 represents the value EPA selected to estimate the forest carbon storage benefit in WARM's GHG emission factors. EPA calculated the results by dividing the change in forest carbon storage in each year by 6.7 million metric tons of pulpwood harvests reduced over the period 2005 to 2009.

Apparently the major driver of the net carbon storage estimate is the time it takes for the increase in carbon storage in live trees and the decrease in carbon storage in downed wood to begin to decline back toward baseline levels. Because the decrease in carbon storage in downed wood returns to baseline levels more quickly than the increase in carbon storage in live trees, the net change in carbon storage actually increases through 2030.

The FORCARB II results indicate that the effect of paper recycling or source reduction on carbon storage appears to be persistent (i.e., lasting at least for several decades). EPA chose to use the value for 2020 in the emission factors, or 1.04 MTCE per metric ton of pulpwood. The choice of 2020 represents a delay of about 5 to 15 years for the onset of incremental recycling, long enough to reflect the effects of the recycling program, but at a rate lower than the peak effect in 2030. As shown in Exhibit 3, the effect is relatively stable over time, so the choice of year does not have a significant effect.

For additional details on this methodology and a comparison of the FORCARB II results to those from other analyses, please see the *Background Document on the Effect of Paper Recycling on Forest Carbon* (Freed et al., 2006).

3.3 CHANGES IN IN-USE PRODUCT CARBON POOL

WARM does not consider changes in the in-use product carbon pool for nondurable goods because these products have shorter lifetimes, typically less than three years, and the carbon contained in these goods cycles out of the in-use pool over a relatively short period.

3.4 NET CHANGE IN CARBON STORAGE

To estimate the rate of forest carbon change per metric ton of paper recovery, multiply the rate of pulpwood harvest (*PWH*) per metric ton of paper recovery (*PRC*) (from Section 3.1) by the rate of forest carbon (*FC*) change per metric ton of pulpwood harvest (from Section 3.2), as shown in Exhibit 4. Exhibit 4 shows the net change in carbon storage per unit of increased paper product recycling, while

Exhibit 5 shows the net change in carbon storage per unit of increased paper source reduction. The various paper grades fall into mechanical or chemical pulp categories as follows:

- Mechanical pulp papers: newspaper, telephone books.
- Chemical pulp papers: office paper, corrugated containers, textbooks, magazines/third class mail.

Note that the net change in carbon storage for recycling and source reduction of wood products (compared with paper products) is different, as discussed in Section 4.

Exhibit 4: Net Change in Carbon Storage per Unit of Increased Paper Product Recycling

(a)	(b)	(c)	(d)	(e)	(f)
Paper Product Recycled	**Reduction in Timber Harvest per Unit of Increased Recycling (Short Tons Timber/Short Ton of Wood) (from Section 3.1)**	**Change in Forest Carbon Storage per Unit of Reduced Timber Harvest (Metric Tons Forest Carbon/Metric Ton Timber) (from Section 3.2)**	**Change in Forest Carbon Storage per Unit of Reduced Timber Harvest ($MTCO_2e$/ Short Ton Timber) (d = c x 0.907 x 3.667)**	**Change in Carbon Storage in In-use Products per Unit of Increased Paper Product Recycling ($MTCO_2E$/Short Ton)**	**Net Change in Carbon Storage per Unit of Increased Paper Product Recycling ($MTCO_2E$/Short Ton) (e = b × d + e)**
Mechanical pulp	0.58	1.04	3.46	NA	2.02
Chemical pulp	0.89	1.04	3.46	NA	3.06

NA = Not applicable.
One metric ton = 0.907 short tons.
One metric ton of carbon = 3.667 metric tons of CO_2e.

Exhibit 5: Forest Carbon Storage from Source Reduction of Paper Products

(a) Material	(b) Mechanical or Chemical Pulp	(c) Reduction in Timber Harvest per Unit of Increased Source Reduction (Short Tons Timber/Short Ton of Wood) (from Section 3.1)	(d) Change in Forest Carbon Storage per Unit of Reduced Timber Harvest (Metric Tons Forest Carbon/Metric Ton Timber) (from Section 3.2)	(e) Change in Forest Carbon Storage per Unit of Reduced Timber Harvest ($MTCO_2e$/ Short Ton Timber) (e = d x 0.907 x 3.667)	(f) Net Change in Carbon Storage per Unit of Increased Source Reduction, 100% Virgin Inputs ($MTCO_2E$ /Short Ton) (f = c × e)	(g) Virgin Inputs in the Current Mix of Inputs[a] (%)	(h) Net Change in Carbon Storage per Unit of Increased Source Reduction, Current Mix ($MTCO_2E$ /Short Ton) (h = f × g)
Corrugated Containers	Chemical	2.11	1.04	3.46	7.26	65.1	4.73
Magazines/ Third-class Mail	Chemical	2.11	1.04	3.46	7.26	95.9	6.96
Newspapers	Mechanical	1.11	1.04	3.46	3.83	77.0	2.95
Office Paper	Chemical	2.11	1.04	3.46	7.26	95.9	6.96
Phonebooks	Mechanical	1.11	1.04	3.46	3.83	100.0	3.83
Textbooks	Chemical	2.11	1.04	3.46	7.26	95.9	6.96

One metric ton = 0.907 short tons.
One metric ton of carbon = 3.667 metric tons of CO_2e.
[a] Source: FAL (2003).

The net forest carbon storage for source reduction of paper products is shown in Exhibit 5. The reduction in timber harvest per unit of increased source reduction (Exhibit 5, column (c)) is the process efficiency of converting pulpwood to finished paper (i.e., 1/ratio of pulp to finished paper), as described in Section 3.1. The net change in forest carbon storage depends on whether the source reduction of paper products is assumed to displace paper that would have been produced from 100-percent virgin inputs or the current industry-average mix of virgin and recycled inputs (FAL, 2003). For source reduction that offsets paper produced from 100-percent virgin pulp, the net change in forest carbon storage is shown in Exhibit 5, column (e). For the case where source reduction offsets paper produced from the current mix of virgin and recycled inputs, however, WARM assumes that the net forest carbon effect is attributable only to the proportion of inputs that are virgin pulp, as shown in Exhibit 5, column (g). WARM makes this assumption because displacing recycled inputs, which have already been harvested from the forest, are unlikely to have a direct effect on forest carbon storage.

4 FOREST CARBON STORAGE AND WOOD PRODUCTS

Wood products in WARM include dimensional lumber, MDF, and wood flooring. These products are long-lived, durable goods that are harvested from sustainably managed soft- and hardwood forests. This section describes the methodology EPA uses to evaluate the three components of forest carbon storage, outlined in Section 2, for softwood products (i.e., dimensional lumber and MDF). The approach for evaluating forest carbon storage for hardwood flooring is similar and is provided in further detail in the Wood Flooring [hyperlink] chapter.

4.1 EFFECT OF SOURCE REDUCTION AND RECYCLING ON TIMBER HARVESTS

To estimate the change in timber harvests that result from increased recycling and source reduction of softwood products, EPA uses estimates provided by Dr. Skog for the system efficiencies (on a weight basis) of producing wood products from virgin inputs or recycled inputs. Assuming that overall demand for softwood products is constant, increases in recycling will reduce timber harvests according to the following ratio:[8]

$$TH = X/Y \qquad \text{(Eqn. 2)}$$

Where,

TH = Change in timber harvests resulting from increased recycling of wood products

X = Process efficiency of converting virgin roundwood into finished wood product

Y = Process efficiency of converting recycled wood into finished wood product

[8] Unlike EPA's consideration of paper products, WARM does not consider exports of recycled wood outside of the United States. In contrast with recovered paper, which is exported to other countries for recycling, recovered wood typically is not directly exported for recycling. Instead, finished wood products or wood packaging materials (such as pallets, skids, containers, crates, boxes, cases, bins, reels, and drums) may be manufactured from recycled materials in the United States for export (Ince 1995; FAO 2005).

Based on the estimates provided by Dr. Skog, EPA assumes that one short ton of finished wood product requires 1.1 short tons of virgin roundwood[9] (i.e., harvested logs, with or without bark), on average, or 1.25 short tons of recycled wood. According to this relationship, each additional short ton of wood products recycled will reduce the demand for virgin roundwood from timber forests by a ratio of 1.1/1.25 = 0.88 short tons.

The effect of source reduction on timber harvests can be calculated from the process efficiency (*X*) of wood products production, assuming that one short ton of source reduction completely offsets virgin roundwood harvests that otherwise would be harvested to produce one short ton of wood products. Section 5 discusses the sensitivity of the forest carbon storage results to this assumption. Consequently, WARM estimates that one short ton of source reduction avoids 1.1 short tons of roundwood harvests for dimensional lumber and MDF wood products.

These values describe the change in timber harvests resulting from increased recycling and source reduction of softwood products. Together with the effects that changes in timber harvests have on forest carbon stocks (developed in Section 4.2), these two parameters describe how forest carbon storage changes as a result of increases in recycling and source reduction. The values developed in this section are also used to determine how source reduction and recycling affect carbon storage in in-use wood products, which is discussed in Section 4.3. The net changes in carbon storage from recycling and source reduction are calculated in Section 4.4, taking into account both changes in forest carbon storage and in-use product carbon storage.

4.2 EFFECT OF CHANGES IN TIMBER HARVESTS ON FOREST CARBON STOCKS

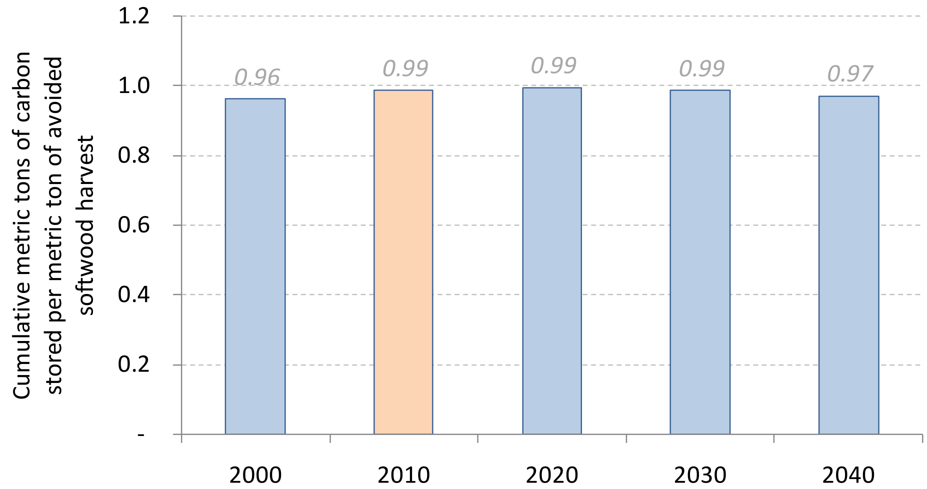
To investigate the change in forest carbon resulting from increased recycling and source reduction of wood products, EPA uses estimates developed from the USDA FS's FORCARB II model. The method for wood products is similar to the approach for paper described in Section 3.2. First, EPA applies a harvest scenario developed in consultation with Dr. Skog and Dr. Linda Heath at USDA FS. EPA determined that the majority of wood products are derived from softwood and evaluated an increased wood recycling/source reduction scenario corresponding to a 1.7-percent reduction in softwood harvest. The 1.7-percent reduction is a representative estimate of the reduction in softwood harvests that could be achieved with a national increase in wood product recycling above current levels.

This reduction is distributed throughout the USDA FS regions in proportion to baseline harvest for the period 1998 to 2007. The cumulative reduction in softwood harvest from the 1.7-percent reduced harvest scenario is 26.4 million short tons over this period.

The effect of this reduction in harvest is to increase carbon sequestration in forests. To be consistent with the approach for paper recycling and source reduction, EPA analyzed effects only for tree and understory components (and excluded forest floor and soils). Exhibit 6 displays the results of the analysis for wood products. The results show that every metric ton of avoided timber harvest results in 0.96 to 0.99 metric tons of forest carbon storage. For consistency with the paper recycling/source reduction analysis, EPA selected the forest carbon storage benefit in 2010, representing a delay of 5 to 15 years from the onset of the simulated period of incremental recycling. This period is consistent with the 5 to 15 year timeframe used in the paper forest carbon analysis in Section 3. Consequently, EPA estimates that a one-metric-ton reduction in timber harvests increases forest carbon storage by 0.99 metric tons.

[9] Harvested logs, with or without bark; roundwood may be round, spilt, or roughly squared (FAO, 1997).

Exhibit 6: Cumulative Change in Forest Carbon Storage per Unit of Reduced Timber Harvest



Note: Colored bar for 2010 represents the value EPA selects to estimate the forest carbon storage benefit in WARM's GHG emission factors. EPA calculated the results by dividing the change in forest carbon storage in each year by 24 million metric tons of pulpwood harvests reduced over the period 1998 to 2007.

4.3 CHANGES IN IN-USE PRODUCT CARBON POOL

The final step involves estimating the effects of increased wood product recycling on carbon storage in in-use wood products.

For recycling, based on the estimates developed in Section 4.1, EPA assumes that 1.25 short tons of recycled wood are required to produce one short ton of finished wood product; in other words, every short ton of wood recycled yields 0.8 short tons of finished wood product (i.e., 1/1.25 = 0.8), and 0.2 short tons of wood are lost from in-use products. For wood products, EPA assumes a carbon density of 0.48 MTCE per short ton of wood, corresponding to softwoods in Southeast and South Central pine forests (Birdsey, 1992). Consequently, the carbon loss from the product pool is given by:

(1 short ton recycled – 0.8 short tons retained) x 0.48 MTCE/short ton x 44/12 $MTCO_2E$/MTCE = 0.35 $MTCO_2E$/short ton

For source reduction of wood products, a short ton of wood offset by source reduction results in a decline in carbon that otherwise would have been stored in the in-use wood product.[10] This essentially represents a one-to-one relationship, where source reducing one short ton of wood avoids one short ton of wood that otherwise would have been manufactured into in-use products. Consequently, the change in the in-use product carbon pool from source reduction of one short ton of wood product is equal to the carbon density of the wood product, given by:

1 short ton source reduced x 0.48 MTCE/short ton x 44/12 $MTCO_2E$/MTCE = 1.77 $MTCO_2E$/short ton

[10] Because dimensional lumber and MDF are not commonly manufactured from recycled inputs in the United States, WARM assumes that source reduction of wood products avoids virgin wood inputs only. This is a different approach than for source reduction for paper products, where the net change in forest carbon storage depends on whether the source reduction of paper products is assumed to displace paper that would have been produced from 100-percent virgin inputs, or the current industry-average mix of virgin and recycled inputs.

Both source reduction and recycling decrease the amount of carbon stored in in-use products; this decrease offsets some of the benefit of increasing storage in forests; see Section 2 for more details.

4.4 NET CHANGE IN CARBON STORAGE

Based on the estimates developed in the previous sections, Exhibit 7 shows the net change in forest carbon storage for recycling and source reduction of wood products. These results conclude that recycling and source reduction of one short ton of wood products corresponds to an increase in net carbon storage. In both cases, the increase in forest carbon storage is offset by a reduction in carbon storage in in-use products as a result of recycling or source reduction.

Exhibit 7: Net Change in Carbon Storage per Unit of Increased Wood Product Recycling

(a)	(b) Reduction in Timber Harvest per Unit of Increased Recycling or Source Reduction (Short Tons Timber/Short Ton of Wood) (from Section 4.1)	(c) Change in Forest Carbon Storage per Unit of Reduced Timber Harvest (Metric Tons Forest Carbon/Metric Ton Timber) (from Section 4.2)	(d) Change in Forest Carbon Storage per Unit of Reduced Timber Harvest ($MTCO_2e$/ Short Ton Timber) (d = c x 0.907 x 3.667)	(e) Change in Carbon Storage in In-use Products per Unit of Increased Wood Product Recycling ($MTCO_2E$/Short Ton) (from Section 4.3)	(f) Net Change in Carbon Storage per Unit of Increased Wood Product Recycling ($MTCO_2E$/Short Ton) (e = b × d + e)
Recycling	0.88	0.99	3.29	-0.35	2.53
Source Reduction	1.1	0.99	3.29	-1.77	1.84

Note: Positive values denote an increase in carbon storage; negative values denote a decrease in carbon storage.
One metric ton = 0.907 short tons.
One metric ton of carbon = 3.667 metric tons of CO_2e.

5 LIMITATIONS

Several limitations are associated with the analysis. The forest product market is very complex, and EPA's simulation of some of the underlying economic relationships that affect the market simplifies some important interactions.

A general limitation of the analysis is that it does not account for any potential long-term changes in land use caused by a reduction in pulpwood or softwood demand, and landowners' choices to change land use from silviculture to other uses. If overall forest area is reduced, this would result in significant loss of carbon stocks. Hardie and Parks (1997) developed an area base model for use in Resource Planning Act assessments to help determine factors that influence land area change. They derived a model that estimated the elasticity of (a) forest land area change with respect to (b) pulpwood price change. They estimated the elasticity to be -0.10, but this was not significant at the 10-percent confidence level. This suggests that forest area change would be limited with a modest price change in pulpwood demand.

The following limitations relate to the estimate of forest carbon storage for paper products:

- Results are very sensitive to the assumption on paper exports (i.e., that paper exports comprise a constant proportion of total paper recovery). If all of the recovered paper is exported, none of the incremental recovery results in a corresponding reduction in U.S. pulpwood harvest. At the other extreme, if all of the incremental recovery results in a corresponding reduction in U.S. pulpwood harvest, the storage factor would be higher. The results are also sensitive to assumptions on the moisture content and the carbon content of pulpwood, pulp, and paper.

- Also, this analysis does not consider the effect that decreases in pulpwood harvest may have on the supply curve for sawtimber, which could result in a potential increase in harvests of other wood products. This could result in a smaller reduction in harvest, offsetting some of the carbon storage benefit estimated here. Prestamon and Wear (2000) investigated how pulpwood and sawtimber supply would change with changes in prices for each. They estimated that non-industrial private forest and industry may increase sawtimber supply when the price for pulpwood increases—and the change is perceived as temporary—although the estimate was not statistically significant. The sawtimber supply, however, may decrease when the pulpwood price increases—and the change is perceived as permanent—but, once again, the estimate was not statistically significant. Given that the relationship between the price change for pulpwood and supply of sawtimber was not consistent and was often statistically insignificant, there is not compelling evidence to indicate that the omission of this effect is a significant limitation to the analysis.
- A related issue is that if the domestic harvest of pulpwood decreases, it could result in a decrease in the cost of domestic production, which could shift the balance between domestic paper production and imports to meet demand.

The following limitations relate to the estimate of forest carbon storage for wood products:

- The estimated changes in timber harvests resulting from increased recycling and source reduction are based on process efficiency estimates that assume overall demand for softwood products remains constant. Increased recycling or source reduction of wood products could increase or decrease demand for new wood products to the extent that these changes influence factors such as virgin wood-product prices. EPA has not explicitly modeled this effect because of the complexity of virgin wood-product markets and the fact that the current assumption provides a first-order estimate of the change in timber harvests from recycling and source reduction.
- Similarly, in-use product carbon storage is modeled based on first-order reductions in carbon storage associated with losses from recycling wood products and avoided in-use product carbon storage from source reduction of wood products. This analysis provides an estimate of the direct, first-order effects on the in-use carbon pool associated with recycling or source reduction of wood products.

As shown in Exhibit 3 and Exhibit 6, estimates of forest carbon storage resulting from increased paper recycling vary over time. As noted earlier, WARM applies a single point estimate reflecting a time period that best balances the competing criteria of (1) capturing the long-term forest carbon sequestration effects, and (2) limiting the uncertainty inherent in projections made well into the future. The variation in forest carbon storage estimates over time and the limitations of the analysis discussed earlier indicate considerable uncertainty in the point estimate selected. In comparison to the estimates of other types of GHG emissions and sinks developed in other parts of WARM, the magnitude of forest carbon sequestration is relatively high. Based on these forest carbon storage estimates, source reduction and recycling of paper are found to have substantial net GHG reductions. Because paper products make up the largest share of municipal waste generation (and the largest volumes of waste managed through recycling, landfill use, and combustion), it is important to bear in mind the uncertainty in the forest carbon sequestration values when evaluating the results of this analysis.

6 REFERENCES

AF&PA. (2010a). *Paper Products Glossary*. Washington, DC: American Forest & Paper Association. Retrieved from http://www.afandpa.org/PaperProductsGlossary.aspx.

AF&PA. (2010b). *Where Recovered Paper Goes*. Annual AF&PA Fiber Survey. Washington, DC: American Forest and Paper Association. Retrieved from http://paperrecycles.org/stat_pages/recovered_paper_goes.html.

AF&PA. (2005). *Wood pulp, recovered paper, pulpwood 25th Annual survey*, 2004–2007. Washington, DC: American Forest and Paper Association.

AF&PA. (2004). 2004 Statistics—Paper, paperboard and wood pulp. Washington, DC: American Forest and Paper Association.

Birdsey, R. A. (1992). *Carbon Storage and Accumulation in the United States Forest Ecosystems*. Washington, DC: U.S. Department of Agriculture Forest Service. Retrieved October 18, 2009, from http://nrs.fs.fed.us/pubs/gtr/gtr_wo059.pdf.

EPA (2011a). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2009.* (EPA publication no. EPA 430-R-11-005.) Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs, April. Retrieved from: http://epa.gov/climatechange/emissions/usinventoryreport.html.

EPA. (2011b). *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2010.* Washington, DC: U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response. Retrieved from: http://www.epa.gov/osw/nonhaz/municipal/pubs/2010_MSW_Tables_and_Figures_508.pdf.

EPA. (2008). *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2007*. United States Environmental Protection Agency, Office of Solid Waste. EPA530-R-08-010.

EPA. (2006). *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2005.* United States Environmental Protection Agency, Office of Solid Waste. EPA530-R-06-011.

FAL. (2003). Personal communication between Randy Freed, ICF International and William E. Franklin, Franklin Associates Limited regarding recycled contents for use in the ReCon Tool. December 10, 2003.

FAO. (2005). *Trends in Wood Products*. Rome: United Nations Food and Agricultural Organization. Retrieved from http://www.fao.org/docrep/008/a0142m/a0142m00.htm.

FAO. (1997). FAO model code of forest harvesting practice. Rome: United Nations Food and Agriculture Organization. Available at http://www.fao.org/docrep/v6530e/v6530e12.htm

FRA. (2004). *Annual Pulpwood Statistics Summary Report, 1999–2003*. Rockville, MD: Forest Resources Association.

Freed, R., Choate, A., & Shapiro, S. (2006). *Revised Estimates of Effect of Paper Recycling on Forest Carbon*. U.S. Environmental Protection Agency (EPA). Retrieved from http://www.epa.gov/climatechange/wycd/waste/SWMGHGreport.html#background.

Hardie, I.W., & P.J. Parks. (1997). Land Use with Heterogeneous Land Quality: An Application of an Area Base Model. *American Journal of Agricultural Economics, 79*, 299–310.

Ince, P. J., McKeever, D. B., & Forest Products Laboratory (U. S.). (1995). *Recovery of paper and wood for recycling: actual and potential.* General technical report FPL-GTR-88.: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. Madison, WI.

Ince, P. J. (1995). *Recycling of Wood and Paper Products in the United States.* General technical report FPL-GTR-89. U.S. Department of Agriculture Forest Service, Forest Products Laboratory. Madison, WI. Retrieved from http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr89.pdf.

IPCC. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Volume 5: Waste, Chapter 3: Solid Waste Disposal. Intergovernmental Panel on Climate Change. Retrieved from http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html

Prestamon, J.P., & Wear, D.N. (2000). Linking Harvest Choices to Timber Supply. *Forest Science 46,* 3, 377–389.

Skog, K.E. (2008). Sequestration of carbon in harvested wood products for the United States. *Forest Products Journal*, 58 (6), 56–72.

VDP. (2008). Papermaking: Information on Raw Materials and Papermaking. Bonn: Verband Deutscher Papierfabrikin e.V. Retrieved from http://www.marketplacepaper.org/pdf/Papermaking.pdf.